Annales Geophysicae Manuscript-No
(will be inserted by hand later)

Comparison of the Wave Energy Transport at the Comets p/Halley and p/Giacobini-Zinner

A. Söding[1], K.-H. Glassmeier[2], S. A. Fuselier[3], Fritz M. Neubauer[1], and B. T. Tsurutani[4]

[1] Institut für Geophysik und Meteorologie, Universität zu Köln, Albertus Magnus Platz, 50923 Köln, Germany

[2] Institut für Geophysik und Meteorologie Technische Universität Braunschweig, Mendelssohnstr. 3, 38106 Braunschweig, Germany

[3] Dept. 9120 Bldg 225, Lockhead Palo Alto Research Lab 3251 Hanover Str., Palo Alto, CA 94304-1191, USA

[4] JPL, 4800 Oak Grove Dr MS 169-506, Pasadena CA 91109, USA

October 18, 1995

Abstract. Using magnetic field, plasma density and flow observations from spacecraft flybys of two comets, Elsässer variables are determined in order to study wave propagation directions. We investigated the inbound path of the Giotto spacecraft flyby of comet p/Halley outside the bow shock (between 10:36 and 19:11 UT on March 13,1986, corresponding to distances from 3.4 x 10^6 km to 1.? x 10^6 km from the nucleus) and the inbound and outbound path of the ICE spacecraft flyby of comet p/Giacobini-Zinner outside of the bow wave (between 00:00 and 9:24 UT and between 12:25 and 23:50 UT on September 11, 1985, corresponding to distance from 8.5 x 10^5 – 1.2 x 10^5 km from the nucleus and from 1.0 x 10^5-9.3 x 10^5 km from the nucleus, respectively). The interaction of cometary pick up ions and the solar wind is expected to generate waves propagating mostly antiparallel to the background magnetic field. The predicted wave propagation combined with observed wave modes generated by the ion cyclotron resonance instability are compared with observed wave properties. Three modes are possible: right-hand polarized waves propagating toward the Sun (RH^-) and left-hand polarized waves propagating toward (LH^-) and away from the Sun (LH^+). Plasma conditions dictate that the RH^- mode is the most unstable mode and we find satisfactory agreement between observed and predicted energy flow directions in regions outside the bow shock at Halley and the bow wave at Giacobini-Zinner, where local cometary ion pickup conditions dominate.

1 Introduction

In 1985 and 1986, ICE and Giotto had their rendezvous with the comets Giacobini-Zinner (G-Z) and Halley, respectively. Analysis of the data from these encounters has resulted in significant advances in the understanding of plasma processes near active comets (see for example the reviews of Neugebauer (1990) and Tsurutani (1991)).

Massloading of the solar wind by cometary ions is the main interaction process in the outer cometary at-

Correspondence to: soeding@geo.uni-koeln.de

mosphere and the solar wind. Neutrals sublimated from the comet surface drifts away from the comet with a velocity of about 1 km/s (Keller, 1976). The neutrals are ionized by photoionization or by charge exchange with solar wind ions. The typical time scale for ionization at 1 AU is of the order of 10^6s. Thus, an extended interaction region is produced. In the solar wind frame the new born ions stream toward the Sun with the solar wind velocity $|\mathbf{v}|$. Due to the Lorentz force, the cometary ions are accelerated perpendicular to $\mathbf{B}$ and gyrate around $\mathbf{B}$. In the solar wind frame they form a ring beam distribution traveling upstream at an initial angle given by

$$\cos\alpha = \frac{\mathbf{v}\cdot\mathbf{B}}{|\mathbf{v}|\cdot|\mathbf{B}|} \quad (1)$$

where α is the angle between the interplanetary magnetic field $\mathbf{B}$ and $\mathbf{v}$ with $0° \leq \alpha \leq 90°$. This beam is unstable and leads to the generation of plasma waves. These waves propagate parallel and antiparallel to $\mathbf{B}$.

The waves interact resonantly with the pick-up ions via the Doppler-shifted ion cyclotron resonance (Tsurutani and Smith, 1986). The initial ring beam distribution of the pick-up ions will be scattered to a bispherical distribution in velocity space by this wave particle interaction. During this process the ions will lose energy which becomes available for wave growth. The energy difference between the ring beam and the bispherical distribution is called free energy and is not immediately released as wave energy as shown by Huddleston and Johnstone (1992) for the comet Halley.

In the present paper we use Elsässer variables to calculate the specific energy densities of waves propagating in opposite directions. This study is based on the assumption that the waves are Alfvénic (non compressive). Using a description of the wave generation under local plasma conditions and based on the ion cyclotron resonance (Thorne and Tsurutani, 1987), predicted and observed energy transport are compared. A case study of this had been already done for Halley (Söding et al., 1995). Here, we compare the results from the Halley encounter with new results from the G-Z encounter.

2 Wave energy transport

Elsässer (1950) introduces variables to simplify the magnetohydrodynamic equations. These Elsässer variables are defined by (Tu et al., 1989)

$$\mathbf{Z}^{\pm} = \mathbf{v} \pm \mathbf{v}_A \quad (2)$$

where $\mathbf{v}_A$ denotes the vector Alfvén velocity. For a homogeneous and incompressible plasma, $\mathbf{Z}^{\pm}$ describe the two possible Alfvénic wave modes propagating in opposite directions which may possible interact non-linearly with each other. Each wave mode could have a different origin, so it is possible to investigate the evolution of two different physical processes.

Shear Alfvén waves propagate parallel and antiparallel to the magnetic field $\mathbf{B}$ at the Alfvén speed. Therefore the Alfvén relation $\mathbf{Z}^{+} =$ const. characterizes waves propagating parallel to the background magnetic field $\mathbf{B}_0$ and $\mathbf{Z}^{-} =$ const. for antiparallel propagating waves.

In the undisturbed solar wind at 1 AU waves are most often observed to propagate away from the Sun (Belcher and Davis, 1979) .

Here we used only the fluctuating part of the Elsässer variables $\delta Z^{\pm} = \delta \mathbf{v} \pm \delta \mathbf{v}_A$. The specific energy densities of the wave modes, the total energy density and the normalized cross helicity are defined by (Marsch and Mangeney, 1987)

$$E^{\pm} = \frac{1}{2} \delta Z^{\pm} \cdot \delta Z^{\pm} \tag{3}$$

$$E_{tot} = \frac{1}{2} \left(E^{+} + E^{-} \right) \tag{4}$$

$$\sigma_c = \frac{E^{+} - E^{-}}{E^{+} + E^{-}} \tag{5,}$$

Thus E^+ describes the energy density of wave propagating antiparallel to B_0 and E^- vice versa. If the ambient magnetic field is directed away from the Sun, E^+ describes the energy density of wave propagating towards the Sun and E^- away from the sun.

The Elsässer ratio $R_E = E^- / E^+$ indicate the mean direction of the Alfvén waves. For $R_I > 1$ waves propagating parallel to $\mathbf{B}_0$ dominate and for $R_I < 1$ it is the opposite case. For $|\sigma_c| > 0.7$ there is one strong Alfvén wave and for $|\sigma_c| < 0.7$ there are two Alfvén waves propagating in opposite directions.

In our analysis we used data from the Giotto and the ICE spacecraft. For Halley data from the magnetometer (MAG) and the Johnstone plasma analyser (JPA) are used (Neubauer et al., 1986, Johnstone et al., 1986). The magnetic field and the plasma data as well are given as a 3 component vector, the temporal resolution is 8s and they are given in a Halley solar ecliptic (HSE) coordinate system. In this coordinate system, the X axis points towards the Sun along the Sun-comet line, the Y axis is antiparallel to the direction of planetary orbital motion and the Z axis completes a right handed coordinate system.

For G-Z, data from the magnetometer and the solar wind electron instrument are used (Bame et al., 1986, Frandsen et al., 1978). The plasma parameter are based on 2-D electron measurements in the spin plane of ICE with a temporal resolution of 24s. The magnetic field data are averaged over the same interval, but they are given as a 3 component vector in a spacecraft centered solar ecliptic system. The X axis points toward the Sun and the Y axis toward dusk. The spin axis was perpendicular to the ecliptic within an accuracy of 0.5 degrees, thus defining the Z axis. Since two component plasma measurements only are available, all derived quantities for G-Z are determined in the spin plane X,Y only.

We have used only data upstream from the bow shocks. For Halley we investigate only the inbound leg. The bow shock is observed on March 13, 1986 at 19:23 UT corresponding to a distance of 1.15x 10^6 km from the nucleus (Neubauer et al., 1986). We have investigated the region from 3.3 x 10^6 km to 1.2 x 10^6 km to the comet (from 10:36 UT to 19:08 UT). For G-z the bow waves inbound and outbound are observed on September 11, 1985 at 9:30 UT and 12:20 UT, respectively corresponding to distances of 1.16 x 10^5 km and 0.96 x 10^5 km from the nucleus. Inbound we investigate the time interval between 00:00 UT and 9:24 UT (8.2 x 10^5 -- 1,2 x 10^5 km) and outbound between 12:25 UT and 23:30 UT (1.1 x 105- 9.3 x 10^5 km). The spatial scale for Halley is one or-

Table 1. Halley inbound path, sign(B · v) = +1

Time	Distance in 10^6 [km]
10:57:22-11:00:42	3.21 - 3.20
11:34:10-11:59:46	3.06 - 2.95
12:03:54- 12:05:30	2.94 - 2.93
14:40:34- 14:49:54	2.30 - 2.26
14:53:38-15:24:26	2.24 - 2.12
15:31:22- 15:38:50	2.09 - 2.06
15:40:02-15:42:34	2.05 - 2.04
16:11:14- 19:08:02	1.92 - 1.20

Table 2. G-Z inbound path, sign(B · v) = +1

Time	Distance in 10^3 [km]
00:00:49- 00:02:01	824-822
00:10:25-00:58:25	812 --75:<
01:17:37-09:22:01	729-. 126

der of magnitude greater than that for G-Z. The reason for this scale difference is the different gas production rates at the two comets, Q = 2×10^{28} molecules/s at 1.03 AU for G-Z (von Rosenvinge et al., 1986) and $Q = 7 \times 10^{29}$ molecules/s at, 0.89 AU for Halley (Krankowsky et al., 1986).

Table 3. G-Z outbound path, sign(B · v) : +1

Time	Distance in 10^3 [km]
12:28:36- 12:57:00	107- 142
13:01:48-15:15:24	148-314
15:17:48 – 16:36:36	317- 415
16:51:00 - 17:01 :24	433-446
17:56:12-18:18:12	514-547
19:37:00-19:43:24	640- 648
19:47:48-19:51:24	652-658
20:37:48-23:3012	716 – 930

At all three investigated passages the magnetic field primarily points away from the Sun. This is shown later by the sign of B · v. The intervals and distances where B is directed away from the Sun are given in the Tables 1, 2 and 3 for 8 s and 24s averages, respectively. In the calculated spectra for Halley, B_0 is directed towards the Sun only between 10:36 UT and 11:10 UT (3.3×10^6 – 3.2×10^6 km) and around 15:09 UT (2.2×10^6 km) and for the inbound leg of G-Z B_0 is always directed away from the Sun. On the out bound path of G-Z except for 16:41 UT to 20:31 UT (4.2×10^5 – 7.1×10^5 km) B_0 points away from the Sun.

To compute the energy density spectra we used 512 data points for the Fourier transform in the case of Halley and in case of GZ 128 successive points with a running average over 5 and 3 estimates, respectively.

In Fig. 1 and Fig. 2 the specific and total energy densities, the Elsässer ratio and the normalized cross helicity integrated over the frequency rangea 1–3 mHz and 3-60 mHz as a function of the distance to the nucleus are shown. In the frequency range 1–3 mHz (Fig. 1) no influence depending on the distance to the comet is observed. $E^- > E^+$ indicates that waves propagating parallel to B_0 dominate. The total energy density is roughly constant. In the frequency range 3-60 mHz (Fig. 2) the influence of the comet is clearly visible. This is the frequency range at and above the gyro frequency of the water group ions (2- 5 mHz during this interval). The energy density of waves propagating parallel to B_0 is constant in this frequency range, but the energy density of the antiparallel waves increases during the approach.

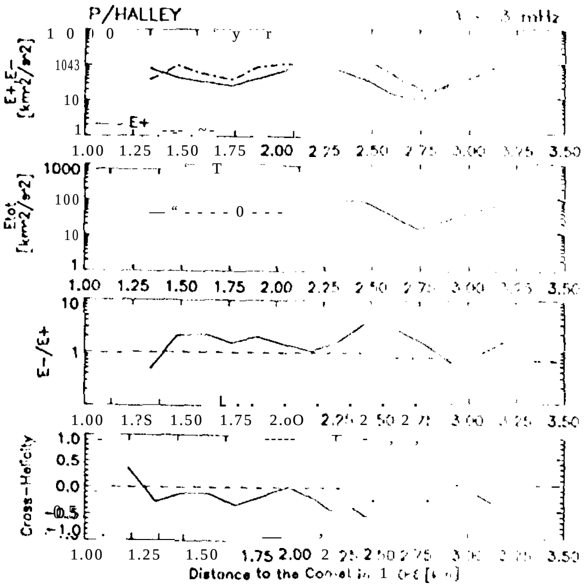

Fig. 1. Specific and total energy densities, Elsässer ratio and normalized cross helicity at comet Halley for the frequency range 1-3 mHz at the inbound. E^+ describes waves propagating antiparallel to B_0 and E^- vice versa. No dependence of the distance is observed.

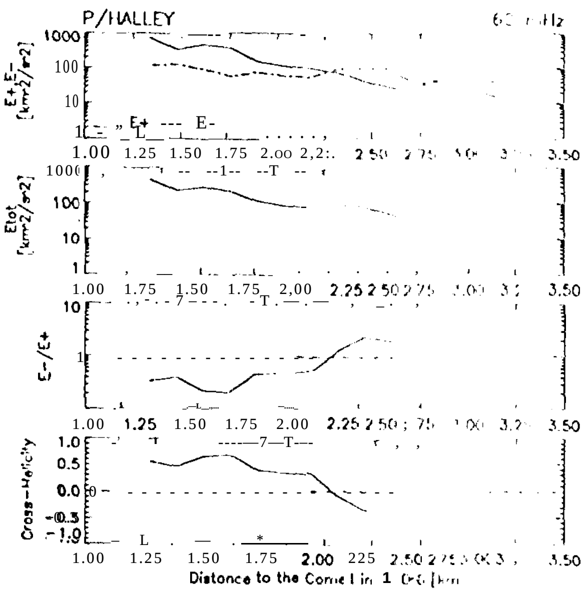

Fig. 2. As Fig. 1, but for the frequency range of 30 mHz above the gyro frequency of water group ions. A dependence of the distance is observable for E^+, but not for E^-.

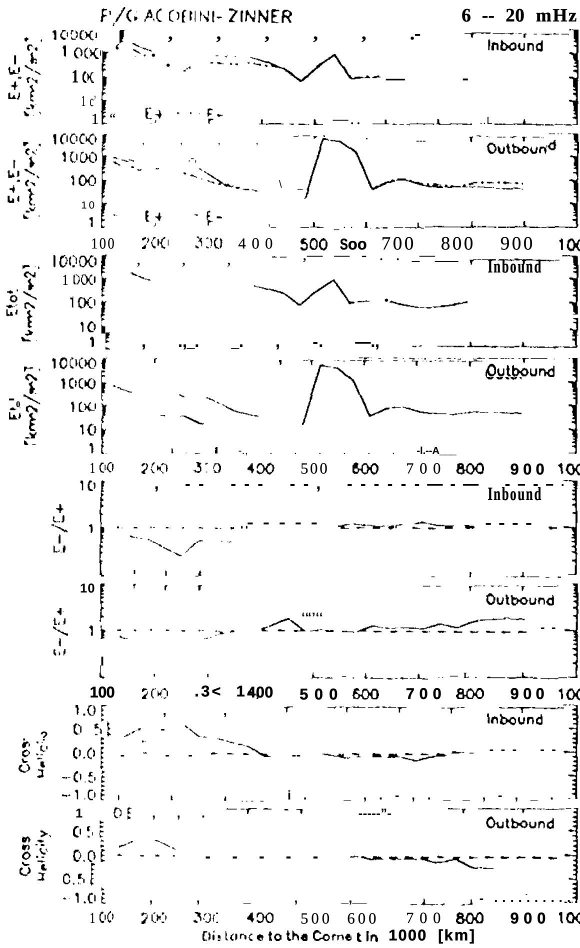

Fig. 3. As Fig. 1 but for the frequency range 6-20 mHz above the water group ion gyro frequency and both at the inbound and the outbound leg of Giacobini-Zinner.

Outside of 2.3 $\cdot 10^6$ km waves propagating away from the Sun (parallel to B_0) dominate and closer to the comet waves propagating toward the Sun (antiparallel to B_0) dominate. This dependence of the distance to the comet is also shown in the Elsässer ratio and in the normalized cross helicity. Close to the comet the cross helicity is relatively high (~ 0.6), but there are still two wave modes propagating in opposite directions. The increase of E_{tot} during the approach is due to the increase of E^+.

For G-Z the results are not as clear as for Halley, but a similar dependence of the distance is at both comets. The gyro frequency of the water group ions is about 7 mHz on the inbound and about [illegible] mHz on the outbound leg. In Fig. 3 the specific and total energy densities, the Elsässer ratio and the cross helicity for the range 6 - [illegible] mHz for both inbound and outbound are shown. Note that all the variables are calculated only in the spin plan and the part of the fluctuations outside the ecliptic plan are not taken into account. The same evolution is clearly visible for the inbound and the outbound path. Up to 450,000 km to the comet the following relations hold: $E^+ \approx E^-$, $R_E \approx 1$ and $|\sigma_c| \approx 0$. Assuming no compressive waves, this result is explained by the presence of two oppositely propagating equal amplitude waves. On the other hand nonlinear compressive waves may perhaps give the same results. However, E^- tends to be a little bit higher than E^+ throughout this period. Closer to the comet the relations change to: [illegible] E^-, $R_E < 1$ and $|\sigma_c| > 0$. In this case the increase of E_{tot} is carried by E^+ and E^-. Therefore closer to the comet waves propagating towards the Sun dominate and far away from the comet waves propagating away from the Sun tend to be slightly more important.

The peak outbound around 550,000 km is caused by a decrease of B to 2.5 nT in this region.

In summary we observed the similar phenomena for Halley and G-Z for fluctuations with frequencies higher than the water group ion gyro frequency. At greater distances from the comets the dominant waves propagate parallel to the background magnetic field B_0 (which points mostly outward from the Sun). In case of G-Z the specific energy density of these waves is only a slightly larger than that for the antiparallel waves. But closer to the comets the Elsässer ratio reverses. Up to distances of 2.3×10^6 km for Halley, 4.4×10^5 km inbound of G-Z and 3.9×10^5 km outbound of G-Z, waves propagating antiparallel to B_0 dominate. Close to the comets B_0 is directed away from the Sun in all three cases in Fig. 2 and 3, so the most unstable waves are propagating towards the Sun. The cross helicity of G-Z is clearly smaller than for Halley close to the comet. The reduced cross helicity implies that waves propagating in opposite directions are generated at G-Z whereas antiparallel waves are more dominant at Halley. This effect is also seen in the increase of E^- during the approach at G-Z. Although the energy densities are compared at G-Z, in two dimensions only, they are 5 times bigger than at Halley, indicating that stronger waves were generated at G-Z compared to Halley (Tsurutani, 1991).

3 Observed and predicted wave properties

Due to the ion cyclotron instability the cometary ions interact resonantly with the plasma waves and will be scattered in pitch angles. Thorne and Tsurutani (1987) have provided a description for the conditions under which this occurs (see also Neubauer et al. (1993), Soding et al., 1995). Three wave modes are possible. In the solar wind frame, these are right-hand polarized waves travelling towards the Sun (RH^-) and left-hand polarized

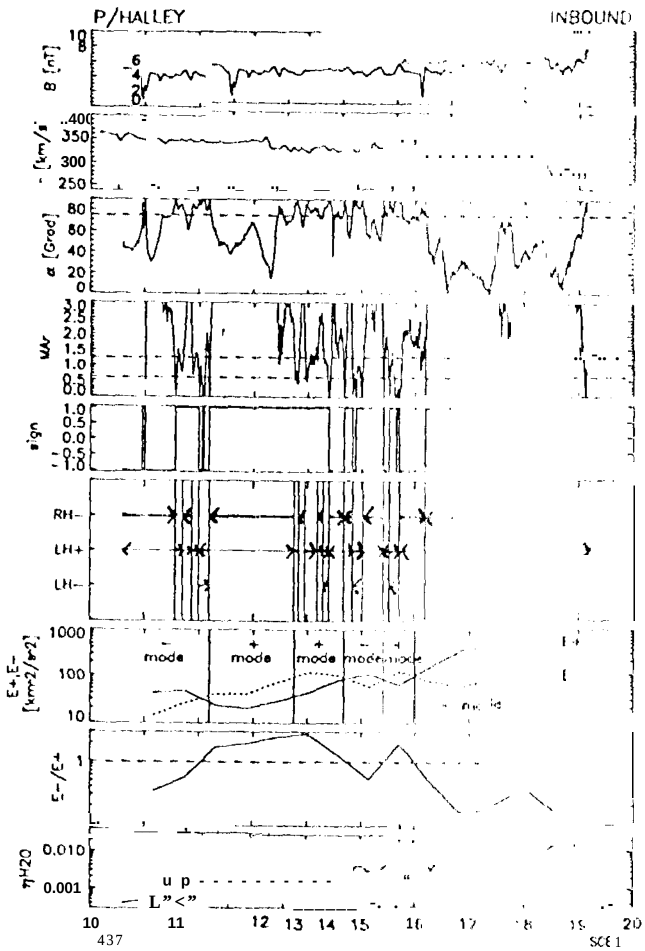

Fig. 4. The magnetic field magnitude B, the solar wind velocity v, the angle α, the Alfvén-Mach number M_{Ar}, the sign of B · v and the relative number density of heavy water group ions η_{H_2O} as a function of time are displayed for the inbound path of Halley upstream of the bow shock. One panel shows the presence of theoretically predicted RH^-, LH^+ and LH^- wave modes by presence of arrows. In the seventh and eighth panel are the specific energy densities $E^{\pm}$ of waves propagating towards and away from the Sun and the Elsässer ratio E^-/E^+ shown. In fact of the observations expected wave modes are signed by "+" mode and "-" mode. See also text.

waves propagating towards (LH^-) and away from the Sun (LH^+).

From the ion cyclotron resonance condition to, ther with a two component cold plasma model with solar wind protons and heavy water group cometary ions Thorne and Tsurutani (1987) obtain a resonance condition depending on the dimension-less field aligned Alfvén-Mach number $M_{Ar} = v_{sw} \cdot \cos\alpha / v_A$. This condition depends also on the heavy ion mass m_+ and the relative number density of heavy ions η_+. Near the bow shock of Halley $m_+ = 18$ (H_2O ions) and $\eta_+ \approx 10^{-2}$ were observed whereas of comet G-Z $m_+ = 18$ and $\eta_+ \approx 10^{-1}$. In the interaction region of the comet with the solar wind η_+ decreases exponentially with increasing distance to the comet. This leads to constraints for the excitation of various wave modes. Resonant RH^- mode waves below a minimum value of M_{Ar} (which depends on η_+) are no longer excited While for the LH mode no limitation on the excitation with respect to M_{Ar} exists. At the same time different waves modes can be generated. As these waves grow to large amplitudes and compete for the available free energy, the instability with the largest growth rate will survive.

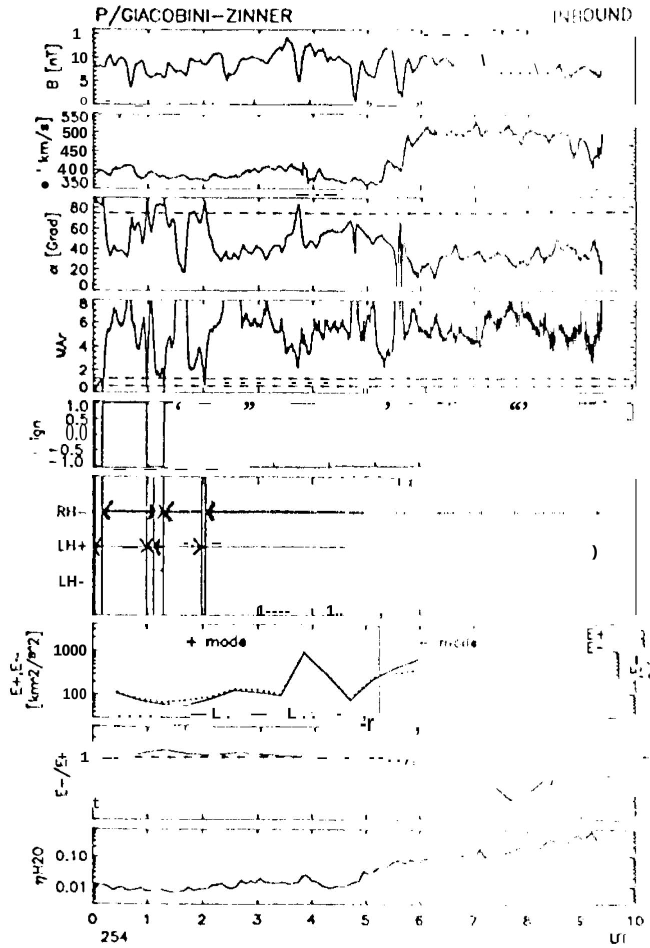

Fig. 5. As Fig. 4, but for the inbound path of Giacobini-Zinner. All variables are only calculated from two dimensions.

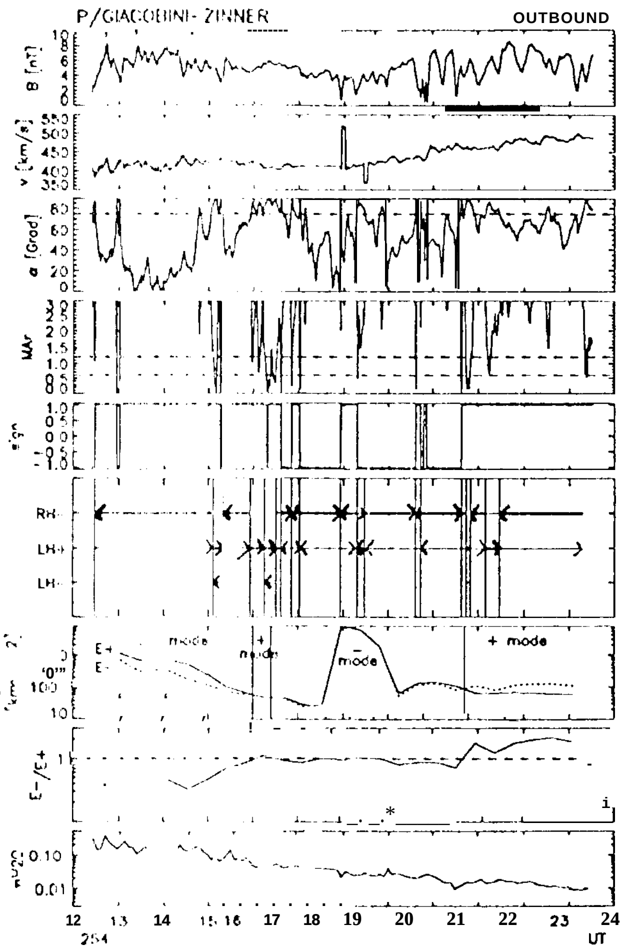

Fig. 6. As Fig. 5, but for the outbound path of Giacobini-Zinner.

From Fig. 4 and 5 of Thorne and Tsurutani (1987) (see also Neubauer et al. (1993), Söding et al (19[illegible])) the conditions of theoretically predicted wave modes are follows: for Halley for $M_{Ar} > 1.25$ and for G-Z for $M_{Ar} > 1.25$ RH^- mode exists and is always dominant for $30° \le \alpha \le 75°$; for $M_{Ar} < 0.6$ the LH^- mode will be excited; the LH^+ mode exists for any M_{Ar} except for $\alpha = 90°$. Its wave growth rate, larger than that of the LH^- mode, if both are excited, and larger than that of the RH^- mode, if $\alpha \ge 75°$. The Fig. 4, 5 and 6 show the magnitude of the magnetic field $\mathbf{B}$, the solar wind velocity v, the angle α, the field aligned Alfvén-Mach number M_{Ar}, the sign of $\mathbf{B} \cdot \mathbf{v}$. In case of $sign(\mathbf{B} \cdot \mathbf{v}) = +1$ the magnetic field is directed away from the Sun and vice versa for $sign(\mathbf{B} \cdot \mathbf{v}) = -1$. In the lower panel the relative number density of heavy water group ions η_{H_2O} is shown. For the calculations we used the model of Huddleston et al. (1990). The sixth panel indicates the presence of the theoretically predicted wave modes RH^-, LH^+ and LH^- by the arrows. LH^+ describes a wave mode propagating away from the Sun and

RH and LH^- towards the Sun. The bolder arrows have the largest wave growth rate and are therefore the wave mode expected to dominate. Arrows pointing from right to left arc antiparallel to B_0 and arrows from left to right parallel. Two other panels display the specific energy densities $E^{\pm}$ and the Elsässer ratio $\frac{J}{J}$, for the fre - quency range 3-60111112 in case of Halley and 6:0 mHz in case of G-Z. To compare the predicted wav mode with $E^{\pm}$ with respect to the Sun, it i. necessary to use $-B$ instead of B, if the radial component of B is directed towards the Sun. 'l'he times where this happens are indicated in the sign panel and have been mentioned above. The expected wave mod are marked with "-1 mode" if $E^- > E^+$ and with "- mode" if $E^+ > E^-$ in these panels.

The results of Fig. 4 at Halley are briefly summarized here, since they have been described .1, detail in Söding et al. (1995). In general observed and predicted energy flow directions agree, except between 12 I and 13:44 UT where there is a clear disagreement in this interval, the observed is a "+" mode and predicted a " " mode. During this time in the water group ion distribution the ions are not observed at the local point of pick up, Söding et al. (1995) conclude that the Naves have been generated under pick-up conditions t h t were different from the local observed conditions

During the inbound trajectory at G Z (Fig. 5) the RH mode is expected to be excited during the intervals 00:10-1:59 and 2:03-9:24 UT and it a ways has the largest wave growth rate except between 1:07 and 1:17 UT. Only between 00:00 and O(J 1011'1', 1:07 and 1:17 UT and 1:59 and 2:03 UT the LH^+ mode is expected to be the dominant one. The LH^- mode should never be excited. The observations show a " -" mode between 5:15 and 8:58 UT and a "+" mode during times before. Indeed in case of noncompressive waves the Elsässer ratio indicates in the earlier region the existence of two wave modes with opposite propagation directions, but with nearly the same energy densities. The theoretically prediction and the observations agree only in the region close to the comet where the " —" mode is observed. Further away when $E^+ \sim E^-$ no agreement is found.

On the outbound path of G-Z (Fig. 6) the situation is more complicated. The RH is expected during the time intervals 12 28 15:07, 15:19-15:56, 16:31-20:44 and 70:5323:17' UT Only during 16:31-16:37,18:19-18:28 ancl 21:09 21:28 UT the RH^- mode does not have the largest growth wave rate and is not expected to be dominant at these times. The LH^+ mode is expected to be excited and to be dominating between 15:07 and 15:19, 15:56 and 16:37, 18:19 and 18:28, 20:44 and 20:50 and 21:09 and 21:28 UT. The LH^- mode is only expected for 3 short time intervals. The observations shows the "- " mode between 12:51 and 16:00 and 16:24 and 20:42 UT and the ' +" mode during the interval 16:00-16:24 and 20:42-23:05 UT For the observed "--" mode a clear agreement with the theory is found, also for the "+" mode between 1 6 O(I and 16:24 UT. A discrepancy is observed during 20:42 and 23:05 UT.

Thus at G-Z like at Halley, there is agreement between observations and predictions in the regions close to the comet. But the question arises, why at G-Z only inside of 433,000 km (5:15 UT) inbound and inside of 720,000 km (20:42 UT) outbound?

The relative number of the heavy water group ions η_{H_2O} shows a dependence of the distance to the comet which can answer these questions. Between 0:00 and 5:00 UT inbound and 20:30 and 23:30 UT outbound η_{H_2O} is nearly constant, During further approach η_{H_2O} increases exponential. For this time interval we found the correspondence of the predicted and observed wave modes. This implies that the region of the influence of the comet to the generation of waves is limited through the noticeable increase of η_{H_2O}. Outside of this the influence of the pick-up ions could be neglected and the fluctuations may be intrinsic to the undisturbed solar wind. These Fluctuations are most often propagating away from the Sun (Belcher and Davis, Jr. , 1971).

Similar studies have been done at p/Grigg-Skjellerup, were the plasma conditions are quite different than at Halley and G-z. Neubauer et al. (1993) predicted RH^- and LH^+ modes upstream of the bow shock and Glassmeier and Neubauer (1993) observed left hand polarized waves in these regions in the peak spectral power in the magnetic field.

4 Discussion and Summary

The regions upstream of the bow shocks inbound leg of Giotto to comet p/Halley and the inbound and outbound legs of ICE to comet p/G-Z are compared with respect. to wave energy transport. During all the time intervals similar plasma condition are observed. Close to the bow shocks the magnetic field is quasi-parallel (α < 45°) and it is further outside qua.si-perpendicular (α > 450). This indicates that one expects similar waves and similar waves are observed.

The specific energy densities $E^{\pm}$, the total energy density E_{tot} as well as the Elsässer ratio and the cross helicity for frequencies higher than the gyro frequency have the same dependence on the distance to the nucleus at the two comets but on different scales. The factor of 35 greater gas production rate at Halley compared to G-Z produces an interaction *region* that is a factor 10 larger. In the interaction regions, mostly waves propagating antiparallel to B_0 are generated with B_0 pointing away from the Sun. This is clearly seen during the whole region investigated, but also at G-Z for distances closer than 4.4×12:' km inbound and 3.9 x 10^5 km outbound. Further outside of G-Z the energy density of the fluctuations propagating in opposite directions are nearly the same and the influence of the cornet could be neglected.

The comparison of the observed wave energy transport directions with the predicted RH^-, and LH^+ and LH^- modes owing to the ion cyclotron resonance indicates in general a good agreement inside of the influence region of the comet. In all three passages the RH^- mode have been driven unstable by the pick-up ion instability. The analysis of the Elsässer variables leads to regions of influence at G-Z up to 4.3 x 10^5 km inbound and 7.2×10^5 km out bound and at the inbound path of Halley up to 4.4×10^5 km which was previously investigated.

Acknowledgement. We thank R.v. Stein for helpful discussions. Also we thank Alan Johnstone for the use of th?.if'), and the members of the experiments for the support the magnetometer and the JPA experiments on Giotto and the magnetometer and plasma experiments on ICE. The work by A.S., K.H.G. and F.M.N. was supported financially by DARA Research at Lockhead was funded by the independent Research Program. The work by B.T.T. was done at the Jet Propulsion Laboratory under contract with the NASA.

References

Bame, S. et al., Comet Giacobini-Zinner: Plasma description, *Science*, 232, 356361,1986.

Belcher, J. and L. Davis, Jr., Large amplitude Alfvén waves in the interplanetary medium, ?, *J. Geophys. Res.* 76(16), 3534, 1971.

Elsässer, W., The hydromagnetic equations *Phys. Rev. A*, 79, 183, 1950.

Frandsen, A., B. Connor, J. Amersfoort and E. Smith, The ISEE-C vector helium magnetometer, *IEEE Trans. Geosci. Electron.*, GE-16, 195, 1978.

Glassmeier, K. and F. Neubauer, Low frequency electromagnetic plasma waves at comet P/Grigg-Skjellerup: Overview and spectral characteristics, *J. Geophys. Res.* 98, 936, 1993.

Huddleston, D., A. Johnstone, and A. Coates, Determination of comet Halley gas emission characteristics from mass loading of the solar wind, *J. Geophys. Res.* 95(A1), 21-30, 1990.

Huddleston, D.E. and A. D. Johnstone, Relationship between wave energy and free energy from pickup ions in the comet Halley environment, *J. Geophys. Res.*, 97, 12217-12230, 1992.

Johnstone, A. et al., Ion flow at comet Halley, *Nature* 321, 344-347, 1986.

Keller, H., The interpretation of ultraviolet observations of comets, *Space Sci Rev.*, 18, 641, 1976.

Krankowsky, D. et al., In situ gas and ion measurements at comet Halley, *Nature*, 321, 326-329, 1986.

Marsch, E. and A Mangeney, Ideal MHD equations in terms of compressive Elsässer variables, *J. Geophys. Res.*, 92(A7), 7363-7367, 1987.

Neubauer, F. M., K. H. Glassmeier, A. J. Coates, et al., Low frequency electromagnetic plasma waves at comet P/Grigg-Skjellerup: Analysis and interpretation, *J. Geophys. Res.*, 98(A12), 20,937-20,953, 1993.

Neubauer, F. M., K.-H. Glassmeier, M. Pohl, et al., First results from the Giotto magnetometer experiment at comet Halley, *Nature*, 321(6067), 352-355, 1986.

Neugebauer, M., Spacecraft observations of the interaction of active comets with the solar wind, *Rev. Geoph*, 28(2), 231, 1990.

Söding, A., K.-H. Glassmeier, A. Johnstone, and F. Neubauer Pick-up ions and associated wave energy transport at comet p/Halley: A case study, *Geophys. Res. Lett.*, in press, 1995.

Thorne, R. M. and B. T. Tsurutani, Resonant interactions between cometary ions and low frequency electromagnetic waves, *Planet. Space Sci*, 35(12), 1501-1508, 1987.

Tsurutani, B. T., 1991. Comets: A laboratory for plasma wave instabilities In A D. Johnstone (Ed.), *Cometary Plasma Processes, Geophys. Monogr.* Ser., Volume 61, Washington D. C., pp 189-210. AGU.

Tsurutani, B. T. and E. J. Smith, Hydromagnetic waves and instabilities associated with cometary ion pickup: ICE observations, *Geophys. Res. Lett.*, 13, 263-266, 1986.

Tu, C.-Y., E. Marsch and K. Thieme, Basic properties of solar wind MHD turbulence near 0.3 AU analyzed by means of Elsässer variables, *J. Geophys. Res.*, 94(A9), 11,739-11,759, 1989.

von Rosenvinge, T. T., J. C. Brandt, and R. W. Farquhar, The International Cometary [illegible] to comet Giacobini-Zinner, *Science*, 232, 353 [illegible], 198[illegible]

This article was processed by the author using the LaTeX style file *cljour2* from Springer-Verlag.